

# Correlation effects in the electronic structure of $\text{Mn}_4$ molecular magnet

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We present joint theoretical-experimental study of the correlation effects in the electronic structure of  $(\text{pyH})_3[\text{Mn}_4\text{O}_3\text{Cl}_7(\text{OAc})_3]\cdot 2\text{MeCN}$  molecular magnet ( $\text{Mn}_4$ ). Describing the many-body effects by cluster dynamical mean-field theory, we find that  $\text{Mn}_4$  is predominantly Hubbard insulator with strong electron correlations. The calculated electron gap (1.8 eV) agrees well with the results of optical conductivity measurements, while other methods, which neglect many-body effects or treat them in a simplified manner, do not provide such an agreement. Strong electron correlations in  $\text{Mn}_4$  may have important implications for possible future applications.

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Single molecule magnets (SMMs), made of exchange-coupled magnetic ions surrounded by large organic ligands, represent a novel interesting class of magnetic materials. They are of fundamental interest as test systems for studying magnetism at nanoscale, and interplay between the structural, electronic, and magnetic properties. SMMs demonstrate fascinating mixture of classical and quantum properties: as classical superparamagnets, they possess large anisotropy and magnetic moment, but also exhibit interesting mesoscopic quantum spin effects [1, 2, 3]. Moreover, recent experiments on the electron transport through SMMs [4], and predicted connection between the transport and spin tunneling [5], make SMMs good candidates for interesting spintronics studies. Progress in this area — synthesis of novel SMMs with optimized properties, design and analysis of the transport experiments, possible uses in information processing — demands detailed theoretical investigations of the magnetic and electronic structure of SMMs [6, 7, 8, 9, 10]. Among other factors, the many-body correlations caused by the Coulomb repulsion between electrons, may be important. E.g., in transition metal-oxide systems [11], which share many similarities with SMMs, strong correlations may form the Mott-Hubbard insulating state [12], where the nature of the charge and spin excitations is drastically different from the predictions of standard band-insulator theory. This affects the basic properties of the system (e.g., exchange interactions), and drastically changes charge and spin transport.

In this joint experimental-theoretical work, we present a detailed study of the many-body effects in electronic structure of SMMs  $(\text{pyH})_3[\text{Mn}_4\text{O}_3\text{Cl}_7(\text{OAc})_3]\cdot 2\text{MeCN}$  (denoted below as  $\text{Mn}_4$  for brevity) [19]. We use the cluster LDA+DMFT method [13] which combines the

realistic *ab initio* calculations based on the local density approximation (LDA), and the accurate description of the correlation effects within the cluster dynamical mean field theory (CDMFT). Using the electron gap as a most convenient benchmark, we show that the gap value (1.8 eV) calculated within LDA+CDMFT is in good agreement with the optical conductivity measurements (showing the peak corresponding to vertical transitions at  $\sim 1.8$  eV). The approaches which neglect the electron correlations (LDA), or treat these correlation in a simplified manner (LDA+U [15]), do not provide such an agreement. Based on LDA+CDMFT calculations, we establish that  $\text{Mn}_4$  is a predominantly Mott-Hubbard insulator with strong electron correlations. These correlations are important for description of ground-state properties of  $\text{Mn}_4$  (intra-molecule exchange interactions, spin ground state, etc.) and may be crucial for future studies of transport through  $\text{Mn}_4$  molecules.

It is important to note that DMFT currently provides the most advanced description of the correlation effects, and is actively used to describe correlations in many materials [14]. However, its use so far has been restricted to the systems containing only a few atoms per unit cell [14, 16, 17, 18]. The present work is, to our knowledge, the first example of applying the LDA+CDMFT method to large systems with very low molecular symmetry, containing 80 atoms per unit cell, establishing feasibility of such calculations and reliability of results. Moreover, the LDA+CDMFT method allows studies of the electronic structure of  $\text{Mn}_4$  at finite temperatures.

The family of  $\text{Mn}_4$  SMMs [3, 19, 20, 21] includes different compounds which have structurally similar cores made of four Mn ions located in the corners of distorted tetrahedron, but possess different ligands, and

exhibit different magnetic and electronic properties. The  $(\text{pyH})_3[\text{Mn}_4\text{O}_3\text{Cl}_7(\text{OAc})_3]\cdot 2\text{MeCN}$  molecules studied here contain three ferromagnetically coupled  $\text{Mn}^{3+}$  ions (spin 2) which interact antiferromagnetically with the fourth  $\text{Mn}^{4+}$  ion (spin 3/2), thus leading to the total ground-state spin  $S = 9/2$ .

Electronic structure of many SMMs, including dimers of the  $\text{Mn}_4$  family, has been studied previously using the density functional theory within generalized gradient approximation (GGA) [9, 10]. These methods describe well the magnetic moments of individual ions and magnetic anisotropy energy, but do not take into account the correlation effects, which are important for many transition metal-oxide systems [11], and for SMMs (where the transition metal ions are coupled via oxygens) [6, 7, 8, 22]. As a result, the value of the electronic gap is underestimated, while the magnitude of the superexchange coupling between magnetic ions is seriously overestimated (by a factor of 3 for  $\text{V}_{15}$  SMMs and for  $\text{Mn}_4$  dimers). The electron correlations can be treated in a simplified way by using the LDA+U approach [15], which takes into account the on-site Coulomb repulsion between the electrons (quantified by the energy  $U$ ) and the intra-atomic Hund exchange (quantified by the parameter  $J$ ). The LDA+U calculations [6, 7, 8, 22] have shown that even a simplified account of many-body effects in SMMs leads to much better agreement between theory and experiment: e.g., for  $\text{V}_{15}$ , the electronic gap, positions of the bands, as well as the exchange interaction parameters agree with experiment within 20–30%.

For electronic structure of  $\text{Mn}_4$ , we first used the single-electron LDA and LDA+U methods. The calculations have been performed using the ASA-LMTO (Atomic Sphere Approximation — Linear Muffin-Tin Orbitals) method [23] as reported in our earlier works [6, 7, 8, 22, 24]. Based on the agreement with experiments achieved in Refs. [7, 24], we used the values  $U = 4$  eV and  $J = 0.9$  eV for Mn atoms. The experimentally determined structure was employed. The resulting densities of states (DOS) are given in Fig. 1 with small additional broadening to make a simpler comparison with LDA+CDMFT results. The LDA results, giving finite electron density at the Fermi energy, can not reproduce the correct insulating states of SMMs, and are not discussed.

The LDA+U calculations give a finite gap of 0.9 eV, thus demonstrating the importance of Coulomb interaction effects [26]. However, the calculated gap is much smaller than the experimentally measured one ( $\sim 1.8$  eV for vertical excitations, see below). Also, LDA+U calculations give no information about the dependence of the gap on temperature, and the nature of the gap is unclear: it may be of band origin, magnetic origin, or Hubbard origin (caused by Coulomb repulsion between electrons). Furthermore, the LDA+U scheme predicts correct values for the magnetic moments,  $3.20 \mu_B$  on

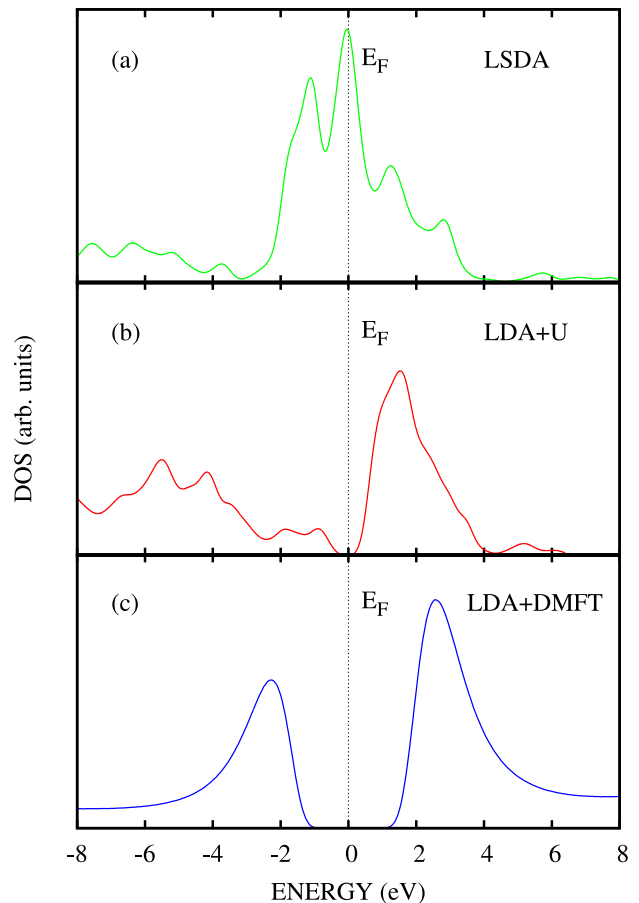


FIG. 1: (Color online). Densities of states (DOS) for Mn 3d orbitals of  $\text{Mn}_4$  calculated using: (a) Local Spin Density Approximation (LSDA); (b) Local Density Approximation taking into account one site Coulomb repulsion (LDA+U) for  $U = 4$  eV,  $J = 0.9$  eV; (c) LDA+CDMFT approach for  $U = 4$  eV,  $J = 0.9$  eV,  $\beta = 8$  eV $^{-1}$ .

$\text{Mn}^{4+}$  and  $4.32 \mu_B$  on  $\text{Mn}^{3+}$  ions. Also, we calculated the exchange parameters  $J_{ij}$  in the Heisenberg spin Hamiltonian  $H = \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$  (where  $\mathbf{S}_i$  are the spins of Mn ions), assuming spin configuration where  $\text{Mn}^{3+}$  spins are directed up, and the  $\text{Mn}^{4+}$  spin is directed down. The calculated couplings between  $\text{Mn}^{4+}$  and  $\text{Mn}^{3+}$  are -29, -14, and -12 K, and the couplings within the  $\text{Mn}^{3+}$  triangle are about 75 K, which is in qualitative agreement with the previously reported exchanges [19, 20]. The exact diagonalization of the Heisenberg exchange Hamiltonian yields the correct  $S = 9/2$  ground state of  $\text{Mn}_4$ , but the excited spin states are not reproduced correctly. Also, the exchange parameters strongly depend on the spin configuration: for ferromagnetic arrangement of all Mn spins (i.e., with reversed spin of  $\text{Mn}^{4+}$ ), the  $\text{Mn}^{3+}$ – $\text{Mn}^{4+}$  exchanges increase by a factor of two. Therefore, the LDA+U scheme provides only a qualitative description of electronic and magnetic properties of  $\text{Mn}_4$ . This is in striking contrast with the  $\text{V}_{15}$  SMM, where the LDA+U

results are in a very good quantitative agreement with a wide range of experiments, from X-ray spectroscopy to magnetic susceptibility measurements [6, 8]. The difference is due to the limited account of the correlation effects by the LDA+U scheme: for  $V_{15}$ , where many-body effects are moderate, LDA+U is adequate, while in  $Mn_4$ , where the many-body effects are very strong, this is not so.

A detailed account of the electron correlations for  $Mn_4$  is achieved by using the dynamical mean-field theory (DMFT) within the cluster LDA+DMFT scheme [13, 16, 17]. Unlike density functional approaches, DMFT considers the total energy of the system (more accurately, the thermodynamic potential) as a functional of the Green's function instead of the density matrix. The analytical properties of the Green's function guarantee that the knowledge of the spectral density is equivalent to the knowledge of the time-dependent Green's function, whereas the density matrix is only static value of the latter. The CDMFT approach maps the many-body crystal system onto an effective self-consistent multi-orbital quantum impurity-cluster problem [13]. The Green's function matrix is calculated via Brillouin zone integration. We down-folded the full LMTO Hamiltonian to the basis of four Mn  $d$ -orbitals in the unit cell and performed CDMFT calculations with the four Mn atoms. We found that hybridization to neighboring Mn atoms in SMM crystal is negligible, and already the first CDMFT iteration gives a reasonable solution of the LDA+CDMFT scheme. The only important quantity which needs to be found self-consistently is the value of the many-body chemical potential, which gives the number of  $d$ -electrons in the  $Mn_4$  cluster.

The cluster impurity solution within LDA+CDMFT method was carried out using the multi-orbital QMC simulations [17] for 4 Mn atoms with full  $d$ -shell basis with the same Coulomb interaction parameters ( $U = 4$  eV), starting from high temperature  $\beta = 8$  eV $^{-1}$  (corresponding to the temperature  $T = 1450$  K) down to the actual experimental temperature  $T = 305$  K ( $\beta = 38$  eV $^{-1}$ ). The value of the gap given by the LDA+CDMFT method is 1.80 eV, twice higher than the gap given by the LDA+U method, and is practically independent of temperature. The DOS were calculated using maximum-entropy continuation from the imaginary time axis, the results are given in Fig. 1c for  $T = 1450$  K [28]. One can see the formation of broad Hubbard bands due to strong interactions between four Mn atoms in the cluster. Note that similar broad Hubbard bands exist in theoretical description and x-ray spectroscopy of manganite compounds [29].

In order to check our LDA+CDMFT calculations, in particular, the value of the gap (which can clearly differentiate between the LDA, LDA+U, and LDA+CDMFT results), we measured the optical properties of  $Mn_4$ . Figure 2 displays the optical conductivity of  $Mn_4$  measured

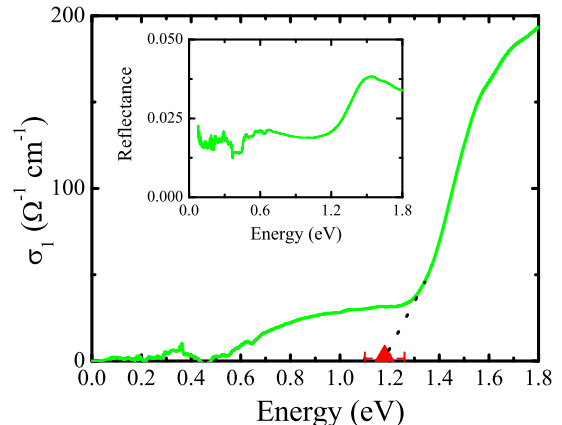


FIG. 2: (Color online) Optical conductivity of  $Mn_4$  at 300 K, obtained from a Kramers-Kronig analysis of the measured reflectance (inset) on the  $[2\bar{2}1]$  crystal face. The red triangle shows the onset of optical absorption due to Mn charge transfer excitations with the corresponding error bar ( $1.18 \pm 0.08$  eV). The peak ( $\sim 1.8$  eV) corresponds to vertical excitations. The residual AC conductivity between 0.6 and 1.2 eV is attributable to the organic constituents.

on the  $[2\bar{2}1]$  crystal face [30]. Based upon the electronic structure results and comparison with chemically-similar model materials, we assign the 1.8 eV peak to a superposition of  $Mn^{3+}$  to  $Mn^{4+}$  charge transfer excitations of the distorted  $[Mn_4O_3Cl]^{6+}$  core and (much lower intensity)  $d$ -to- $d$  on-site excitations of the Mn centers. Interest in microscopic conduction pathways in molecular magnets has motivated several combined transport, optical, and theoretical studies [7, 22, 31, 32, 33, 34]. These investigations showed that exact gap values depend on the nature of the experimental probe and its associated length scale, although overall trends for chemically-similar materials are consistent. While the optical gap in  $Mn_4$  is experimentally determined by extrapolation of the leading edge of the 1.8 eV band to zero conductivity ( $1.18 \pm 0.08$  eV), the peak of this excitation marks the  $\Delta k = 0$  transitions and the maximum in the joint density of states. The peak value ( $\sim 1.8$  eV) should thus be compared with theoretical predictions. The weaker feature between 0.6 eV and 1.2 eV derives from the organic constituents, consistent with data from the  $[3\bar{2}\bar{1}]$  crystal face that has increased sensitivity to these structures.

The agreement between experiment and the LDA+CDMFT predictions, and lack of such agreement for LDA and LDA+U methods, clearly demonstrates the importance of the correlation effects in  $Mn_4$  SMMs. These correlations may persist in functionalized  $Mn_4$  SMMs: deposition of SMMs on the metal substrates may have little effect on their electronic structure (unless charging effects or mechanical deformations occur)

[24, 25]. The correlation effects may also be crucial for transport through  $\text{Mn}_4$ , due to peculiar nature of carriers in Hubbard bands, and for intra-molecular exchanges (which are still too complex for LDA+CDMFT). Our work presents only the first step in this interesting direction, and further studies are required.

Summarizing, we have investigated the correlation effects in electronic structure of  $\text{Mn}_4$  SMMs. Theoretical studies employed (i) the local density approximation, LDA, which neglects the electron correlations; (ii) LDA+U method, which describes correlations in a simplified way; and (iii) LDA+CDMFT method, which provides a detailed account of the many-electron effects within the cluster dynamical mean-field theory. The measurements of the optical conductivity have been used to determine the electronic gap in  $(\text{pyH})_3[\text{Mn}_4\text{O}_3\text{Cl}_7(\text{OAc})_3]\cdot 2\text{MeCN}$ . Among the three theoretical approaches, only LDA+CDMFT predicts a gap consistent with experimental measurements, clearly demonstrating importance of the electron correlations. The LDA+CDMFT calculations evidence the predominantly Hubbard insulator state of  $\text{Mn}_4$ . Based on similarities with other Mn-oxide strongly correlated systems [35, 36], one may expect the correlations to be important for magnetic and transport properties of  $\text{Mn}_4$ .

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